The Potential for Mid-Infrared Astronomy with the Next Generation Space Telescope

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Abstract. While the baseline for the Next Generation Space Telescope (NGST) is the 1 to 5 μm wavelength interval, compelling astronomical observations become possible at longer wavelengths. Significant interest therefore exists in a possible extension of NGST's performance into the mid-infrared (MIR). In the following, a report to NASA on the observations enabled with an MIR-capable NGST is summarized.

1. Introduction

Extending the capabilities of NGST into the mid-infrared (MIR) would vastly enhance the ability of the observatory to address and resolve key scientific questions. The areas most directly impacted by an MIR capability on NGST include the genesis and evolution of galaxies, the nature of luminous galactic nuclei, the star formation process, the life cycle of dust grains in the interstellar medium, the evolution of circumstellar particulate disks, and the detection of thermal emission from planets around nearby stars. These topics can be summarized as the formation of galaxies, of stars, of planetary systems, and of the building blocks of life. The range of topics which can be tackled with an MIR capability on NGST is thus quite broad, and it is crucial to note that several of these topics can *only* be resolved with an MIR-capable NGST. This paper provides a condensed version of a report to NASA (which can be found at http://wwwmipd.gsfc.nasa.gov/isim/science.htm), which details the wide range of scientific issues for which an MIR capability on NGST is crucial. The full report also presents a flexible design concept for an MIR camera/spectrograph, and explores the critical area of cooling detector arrays to operating temperatures below the NGST passive cooling regime. Due to space limitations, here the emphasis is on the astrophysical potential. Generally speaking, the astrophysical investigations which an MIR capability enables fall into two categories: rest-frame MIR emission processes in the local universe, and intrinsically shorter-wavelength emission which cosmic expansion has redshifted into the MIR. In the following, the MIR is taken to be the 5–30 μm wavelength range.

Short MIR wavelengths, $\approx$ 5–10 μm, are especially important to high-redshift (high-z) science for several reasons. First, 5μm is not a true physical limit from the point of view of cosmology: cosmic expansion redshifts a large part of a galaxy's familiar rest-frame near-infrared (NIR) emission into the MIR by $z \sim 2-3$, and even the Hα line, the strongest emission feature in the visual spectrum of most galaxies, shifts into the MIR by $z = 6.6$. Second, since a significant fraction of high-z galaxies are likely to be dusty, the MIR (i.e. the redshifted NIR) will be vital for peering through the obscuring dust, in order to measure true star-formation rates and the ambient star-forming environments at early epochs. Third, in contrast to the NIR, the majority of the 5–10 μm spectral region (5–8 μm) is completely inaccessible from the ground. Finally, the precursor SIRTF mission will have no high resolution spectroscopic capability for $\lambda < 10$ μm. The 5–10 μm spectral band is thus both a natural extension to NGST's core cosmological mission concept, and an area which will remain quite underdeveloped spectroscopically even a decade from now (except for inroads made by SOFIA). It is also a natural extension to lower resolution SIRTF imaging at 3.5–8 μm. Thus a sensitive MIR camera/spectrometer covering at least the 5–10 μm range, with a spatial resolution of order $0.12 - 0.25''$ will enable a revolutionary step forward in high-z studies. NGST's large mirror will provide an MIR spatial resolution comparable to that of the Hubble Space Telescope in the NIR, the VLA in the radio, and the ALMA (Atacama Large Millimeter Array) at millimeter wavelengths, allowing a detailed comparison of star-formation and galactic structure tracers over seven decades in frequency.

However, high redshift science is by no means the whole story, as several areas of "galactic" science are equally, if not more, promising for investigation by NGST in the MIR. The processes regulating star formation, and the origin and evolution of particulate disks and planetary systems around nearby stars are both topics for which longer wavelength MIR observations will be essential, because thermal emission from dust grains cooler than room temperature rises rapidly to longer MIR wavelengths. For example, the spectacular dust ring seen recently about the star HR4796 was discovered by means of its thermal MIR emission, and only later coronagraphically imaged by the HST in the NIR. Such discoveries are likely to follow in rapid succession, as fainter disks and more obscured star-formation sites are systematically discovered and studied. SIRTF will lay the groundwork in this area, as the far-infrared (50–100 μm) will be a very sensitive tracer of faint dust disks. Although SIRTF will be ideally suited to the discovery of such systems, its limited spatial resolution will be inadequate for detailed studies of the structures and evolutionary states of these disks (while ALMA will likely be sensitive to the cooler, larger-scale emission regions). NGST can excel in these areas, but only if it operates out to $\approx$ 30 μm, its longest feasible MIR wavelength, and only if it includes an MIR spectrographic capability. In particular, as ISO has shown, the constituents of dusty disks can be identified by means of their MIR vibrational bands. The vastly higher spatial resolution of NGST, in comparison with both ISO and SIRTF, can then be used to go the next step: by mapping the distributions of the minerals present in circumstellar disks, the different thermal and chemical regimes present can be minerologically delineated. Even higher spectral resolution ($R = \lambda/\Delta\lambda \approx 1000 - 3000$) observations of the H_2 molecule can also be used to trace the gradual disappearance of the gas phase as disks evolve into planetary systems. The combination of high spatial and spectral resolution which NGST can provide can thus revolutionize our view of the formation and evolution of solar systems, and NGST may well see in action the processes which ruled the development of our present day solar system.

A brief overview such as this cannot possibly address every aspect of MIR science made possible with an MIR-capable NGST. In the following we therefore attempt to provide a coherent framework wherein most of the foreseen science can be captured. To this end we have identified seven topics in which MIR NGST observations are crucial:

- Finding and identifying high-z MIR-bright galaxies, in order to determine the true star-formation rate at early epochs.
- Using MIR spectroscopy to evaluate the overall galactic environment in early star-formation sites and the role of central accretion sources.
- Establishing the nature of the stellar populations present at early epochs.
- Delineating the chemical lifecycle of particulate dust, from its origins in the outflowing embers of dying stars, to its incorporation into new planetary systems.
- Peering deep into the hearts of cold molecular clouds in order to trace the process of protostar formation.
- Examining dust disks around nearby stars, in order to place our own solar system into an evolutionary context.
- Surveying the local neighborhood for the coldest brown dwarfs and for extrasolar planets.

The succeeding sections briefly address each of these topics in turn. A more complete discussion of these topics, including a set of illustrative figures, a complete reference list, and a description of a proposed MIR camera/spectrometer, can be found in the full report on the aforementioned web site.

2. The Genesis and Evolution of Galaxies: Unveiling the Hidden Universe with an MIR NGST

In the local Universe, regions of high star-formation activity are often dusty, because the youngest, most massive stars are found close to the molecular clouds out of which they formed. A large fraction of the stellar UV/optical luminosity is therefore absorbed by, and heats up, dust grains in the surrounding clouds. As a result, galaxies with the highest star formation rates tend to emit progressively larger fractions of their luminosities in the thermal IR. This reaches extreme conditions in Ultraluminous Infrared Galaxies (ULIRGs) wherein more than 90% of the luminosity emerges in the MIR and far-infrared (FIR). The discovery of dusty galaxies at high-z with SCUBA and ISO suggests that large populations might remain un-discovered in UV-visual surveys, and that perhaps only a minority of the UV luminosity generated by star formation at high redshifts is detected at all. Indeed, up to half of the expected energy release by nucleosynthesis throughout cosmic time reaches us at FIR and longer wavelengths, implying that star-formation rates inferred from UV and optical observations alone underestimate the true star-formation rates by at least a factor of two (Dwek *et al.* 1998). Thus, the obscuring effects of dust must be taken into account at high-z at least as much as in the local Universe, and so an NGST limited solely to shorter NIR wavelengths might completely miss much of the star formation in the Universe.

To quantify what an MIR-capable NGST would see, expected 10 and 25 μm galaxy counts were simulated with the empirical model developed for WIRE (Xu *et al.* 1998). The model starts with the properties of galaxies detected by IRAS, and computes fluxes and colors at higher z. The model assumes luminosity evolution increasing as $(1+z)^{3.5}$ to $z=2$, and then no evolution for $z>2$. With these conservative assumptions, a 10^5 sec NGST image will detect about 850 galaxies at 10 μm and 150 galaxies at 25 μm in a 70$''$ field. The peak of the red-shift distribution is at $z \sim 2$, and even without evolution at higher z's, there will be a significant high-z tail: over 300 galaxies at 10 μm and 40 at 25 μm with $z \geq 4$. New populations of dusty objects at high-z will thus be easily detectable in even a single deep NGST exposure.

3. MIR Spectral Diagnostics of Galactic Ecosystems

Luminous infrared galaxies ($L_{IR} > 5 \times 10^{11}$ L$_\odot$), while rare in the local Universe, may actually be ideal laboratories in which to study the processes of galaxy building and rapid star formation. These galaxies are nearly always comprised of interacting or merging spiral systems, and since they are extremely dusty, it is critical to observe them at the longest possible wavelengths to uncover buried nuclear energy sources, and to understand the energetics and dynamics of the interstellar medium (ISM) as it responds to the galactic merger and the tremendous energy input via photoionization and large-scale shocks. While the trigger for producing extremely luminous, starbursting galaxies at the highest redshifts may not be identical to that at low-z (namely the merger of two well-formed spirals), the net effects of cycling large amounts of raw material through several generations of stars in a relatively short time, and depositing huge amounts of energy into the ISM, may be quite similar at early and late epochs. MIR spectroscopy offers a set of complementary probes of the interstellar environment in these (and other) galaxies, which can be used to delineate a galactic ecosystem's characteristics, including a host of fine-structure lines, atomic H lines, molecular H_2 lines, and redshifted Fe lines. Above a redshift of $z \sim 1-3$, rest-frame MIR features pass out of the observing window under consideration, but they are replaced by stronger, rest-frame NIR and eventually optical lines which afford further opportunities to study the ionizing sources, the ISM, and the stars themselves in dusty galaxies.

4. Stellar Populations and Galaxy Morphology

An MIR-capable NGST also has a critical role to play in the measurement of young and old stellar populations in galaxies, and in the definition of galaxy morphologies. Most galaxies are made up of a mix of stellar populations, the fraction of young and old stars changing both with redshift (age) and Hubble type. The young stars can be measured directly in the UV (if unobscured), or inferred spectroscopically from their effects on the surrounding ISM (Sect. 3). To see the old stars, however, it is crucial to sample the rest-frame NIR spectrum of a galaxy, where the 1.62 and 2.29 μm CO bandheads lie, and this can only be achieved in the MIR for galaxies at cosmologically interesting redshifts. Such measurements are very important for studies of the evolution of many different types of galactic systems: In galaxies selected to be young (*e.g.*, Lyman break galaxies) one can search for old stars that would signal a previous major episode of star formation. In systems known to be old, or where a massive galaxy is likely already in place (*e.g.*, high redshift radio galaxies and/or QSO hosts) one can search for evidence of significant young stellar populations (also by means of the CO bandheads) that may have been triggered by the passage of radio jets or the merger of galaxies.

At this point, the Lyman break technique has generated hundreds of galaxies at redshifts of $z = 2.5 - 4.0$. As this technique is pushed to longer and longer wavelengths over the next few years, the numbers of known galaxies in the $z = 4 - 7$ range will greatly increase. Presently, the break technique naturally selects for UV-bright, blue galaxies, and therefore is very good at finding rapidly star-forming systems (with some AGN sprinkled in as well). Since the redshifts of these galaxies are close to those during which large galaxies were still being assembled, it is natural to ask whether or not the break galaxies are going through their first episodes of star formation, or whether we are seeing large bursts on top of pre-existing stellar populations. The former would be considered as more "primeval galaxies" while the latter might be more like ultra-luminous infrared galaxies in terms of their star formation rates (although probably not as dusty). Therefore, it is critical to observe these sources at wavelengths well beyond those used to find them in the first place (the rest frame UV) because that is where the old(er) populations will dominate the integrated light. As recent WFPC and NICMOS images of a faint galaxy in the Hubble deep field have highlighted, the best place to look for old stellar populations is in the rest frame H or K bands, because the rest-frame optical emission gives a very biased and incomplete picture of a galaxy. In the images given in Thompson *et al.* (1999), the optical image completely misses the central, bulge-like feature so prominent in the NIR. The resulting morphological disparity can be dramatic at high-z, making an MIR capability critically important.

While the Lyman-break galaxies are a good example, the same arguments apply to any galaxies at $z > 2 - 3$, even the host galaxies of AGN (*e.g.*, QSO's and radio galaxies). It will be easier to detect the host galaxies and measure the old stellar populations (if they exist) in these presumably massive systems by using a high-resolution MIR camera on the NGST. The old stars should not only be present, but they may also have a "relaxed" stellar distribution, similar to an elliptical galaxy today. A luminous old stellar population with a relaxed stellar light distribution at high-z makes a strong argument for a massive galaxy already in place at high-z, and this, in turn, places very strong constraints on the cosmology within which these systems were assembled. For example, Benitez *et al.* (1999) report the detection of a substantial population of $1 < z < 2$ early-type galaxies with old (≥ 2 Gyr) stellar populations, based on recent NICMOS & VLT observations of the HDF-South field.

Even if old, fully-assembled galaxies at $z > 3-5$ are not found, it still might be possible to detect sub-galactic building blocks which formed first, *i.e.*, bulges, and constrain their formation epoch. As discussed above, the best way to find aging bulges at significant z is in the MIR, where the old stars peak and the extinction is at a minimum. Local bulges have K-band surface brightnesses of 16 mag arcsec^{-2}, corresponding to 250 μJy arcsec^{-2}. At z=4, given the cosmological dimming factor, $(1+z)^3$, the surface brightness of these bulges will be ~ 2 μJy arcsec^{-2} or 0.08μ Jy/beam, shifted to the 10μm band. This 10 μm surface brightness should be detectable (S/N ~ 10) in about 16 hours, even with no evolution (brightening) in the bulge surface brightness. The physical sizes of local bulges (*e.g.*, in M31) are ~ 4 kpc, which at z=4 corresponds to an angular size of $0.5''$-$1''$. Such bulges can be resolved with NGST, enabling the study of their light distributions, which may provide important (dynamical) information on when and how bulges form.

Finally, the contribution of accretion-powered energy from AGNs to the total energy density of the universe remains an outstanding unsolved problem, as are the related issues of the first generation of AGNs and the co-evolution of massive black holes and galaxies. Star formation is most often the source of the radiation that heats the warm dust in galaxies, but in active systems, an AGN can heat dust to very warm temperatures and generate blackbody spectra which peak in the MIR. In cases where most of the energy is produced in a small volume (most active galaxies as well as ULIRGs) it is important to have the highest possible spatial resolution to correctly assign the relative fraction of energy produced by hot stars and an AGN. As ISO has shown, MIR spectroscopy is a very good tool to unearth buried power sources, but high resolution MIR imaging has an important role to play here as well. Since an AGN is basically unresolved, while a starburst will extend from several hundred pc to a few kpc in diameter, the size of the warm dust region in the nucleus of an active galaxy can directly constrain the energy source. In this manner, an MIR imager becomes a very powerful tool for probing the central regions of dusty galaxies, and for determining whether the energy is deposited by central accretion or by young, hot stars.

Although deep MIR imaging at high spatial resolution is the easiest way to obtain the initial evidence for an old population of stars in a high redshift galaxy, the ability to measure stellar absorption lines places the study of early galaxy formation and evolution on a much more quantitative footing. Stellar photospheric features in the rest-frame optical and NIR produce strong absorption in the I, H and K-band spectra of galaxies. These features can be used to infer the age and metallicity of the stellar population, as well as the total dynamical mass of the high redshift galaxy. The calcium IR triplet (8498, 8542, 8662 Å), visible at $z \geq 4.8$, is an excellent metallicity indicator for stellar systems with ages ≥ 1 Gyr. The CO bandheads, on the other hand, can be exploited for their sensitivity to the effective temperature of the stars. At even higher redshifts ($z \geq 9$), traditional optical spectral indices such as Hβ, MgII 5175 Å, and Fe 5270 Åcan also be used. Since young starburst galaxies (at ages of 1–few $\times 10^7$ yrs) can have unusually strong CO absorption bands due to the presence of large numbers of red supergiant stars, the simple comparison of the CO band strengths with other diagnostics (*e.g.*, the adjacent Br-γ line equivalent width, or the rest-frame K-band luminosity) can be used to estimate the most important parameters of the burst (age, mass fraction involved, etc). The easiest way to gauge the overall strength of the CO lines is with a low resolution (R$\sim$ 100) MIR spectrograph. In Arp-220-like galaxies, for example, the CO bandhead can be detected out to $z = 4$ in several hours, and out to $z \approx 5$ in 1 day, thus allowing a search for strong CO absorption in the integrated light of galaxies during the time when massive galaxies were first being assembled and star formation was at its peak.

5. The Lifecycle of Interstellar Grains

Interstellar matter provides the basic building blocks from which new solar systems like our own are made. The formation of stars begins with the collapse of a dense interstellar cloud core, a reservoir of dust and gas from which the protostar and circumstellar disk are assembled. The dust particles are typically 0.01–0.1 μm in size, and consist of silicates, oxides and carbonaceous material such as PAHs, formed in the outflows of dying stars. In cold environments, gas-phase molecules condense on the grains and form an icy layer. During the evolution from their formation sites in aging stellar envelopes through their stay in the ISM until their incorporation into new planetary systems, these solid-state species undergo a complex series of physical and chemical metamorphoses. Solid-state vibration-band spectroscopy in the MIR (3–30 μm and longer) is the *only* way to probe this dust lifecycle (van Dishoeck, this volume).

ISO observations of circumstellar disks were limited to only a handful of unresolved disks around intermediate mass stars, but NGST will be able to image such disks in various MIR features around lower-mass, solar-type stars, and to perform absorption spectroscopy of ices and other features toward the highly-extinguished stars behind edge-on disks, such as those embedded in the proplyd disks in Orion. Only an MIR spectrometer on NGST will be able to cover the relevant wavelength range, and to provide the sensitivity and spatial and spectral resolutions necessary to probe the full lifecycle of dust from its formation in dying stars to its incorporation into new planetary systems.

6. Protostars

A protostar is an object which derives its luminosity from the gravitational collapse of a dense, pre-stellar gas and dust cloud core. Understanding how these objects form and evolve is key to understanding the formation of single and binary stars and their accretion disks, which eventually give birth to extrasolar planetary systems. Such rare, short-lived, and extremely obscured protostellar objects were first recognized at submillimeter wavelengths, because the dust in an infalling protostellar envelope (of typical dimension a few thousand AU) reaches very high extinctions ($A_V > 400$), effectively cutting off the spectra in the MIR.To date, all 45 known protostars within 500 pc of the Sun remain either undetected in the MIR, or if detected by ISO, appear as weak (mJy level) point sources. With an MIR capability reaching to 30 μm, NGST can revolutionize our knowledge of the star formation process, by providing us with our first detailed look at the highly obscured, warm (few 100K) inner dust structures closest to the central accreting object.

7. Lifecycles of Disks

Eventually, adolescent stars emerge from their cloudy wombs, allowing more direct observation of disk structures. These young disks lead to planet formation, and so it is vital to study such disks over a range of ages. Spectral models suggest that as young T Tauri (TT) stars begin to lose the H-α signature of disk accretion (*i.e.*, progress from a "classical" to a "weak-line" TT phase), small dust grains initially disappear from the inner disk. It is likely that as molecular gas disappears, viscous accretion fails to replenish grains which spiral into the star. It may also be the case that the grains have aggregated into planetesimals. As this process continues, it becomes impossible to detect residual IR excesses from the ground. It may be that these stars have particulate disks like that around β Pic, but at the distances of the nearest star-forming regions, and at the lower temperatures commensurate with the environments of low-mass stars, they are far more difficult to detect. MIR imaging on NGST can excel at detecting the faint infrared excess from stars at this phase and at resolving structure. This will fill a much-needed gap in our understanding of the post-classical TT evolution of circumstellar disks. In addition, it will be possible to image holes and/or gaps expected in disks in which planets form..

At ages of 10^7–10^8 yr, circumstellar material was detected by IRAS around nearby (10–100 pc) A stars in the thermal IR. A stars are brighter than low-mass stars, and can heat material to temperatures corresponding to MIR wavelengths at larger radii from the star. IR images and spectra of HR 4796, and submillimeter images of Vega, Fomalhaut, β Pic, and ϵ Eridani reveal that, at this phase the disks possess inner solar-system-sized regions in which the density of grains is vastly reduced. These disks are ephemeral; they have persistence timescales that are much smaller than the age of the system. It is theorized that they are maintained by collisional action within a system of planets and planetesimals. Observations of HR 4796A, for example, reveal a radial dust distribution that resembles an enhanced version of our own solar system's zodiacal dust and Kuiper Belt distributions. The presence of planetary bodies embedded in these disks is expected to be evident in the small scale morphology of the dust. Azimuthal asymmetry is already suggested in the 15$''$ resolution JCMT SCUBA images. High-resolution NGST MIR observations will be especially capable of detecting these signatures. For disks like that around Vega, the surface brightness of the dust is too low to be detectable in the MIR from the ground, but NGST MIR observations will be able both to detect and resolve AU-scale details.

Disks in the 10^8 to several $\times 10^9$ year age range are the evolutionary bridge between planet-forming disks and remnant disks like our solar system. NGST MIR imaging and spectroscopy of warm dust around main sequence AFGK stars within 10 pc (combined with ancillary effort to determine stellar ages) can place our system in an evolutionary context, and potentially quickly reveal the dynamical influence of planets. The early part of this span (1 to 5×10^8 yr) corresponds to our heavy bombardment era, during which the terrestrial zone of the planetary system would have had a dust density a few thousand times the present value, presenting a strong MIR signal from collision debris. Assuming a flat age histogram, $\approx 10\%$ of nearby stars should fall in the heavy bombardment age range. There is a controversy about whether this heavy bombardment was simply the tail of the planet accretion process or a discrete event caused by the final construction of the outer planets and the scattering of planetesimals across the solar system. It is probably significant that life did not begin on earth until the bombardment ended. Heavy bombardment is also a possible means of introducing much of Earth's biospheric organics. Finally, low upper limits on warm (terrestrial-temperature) dust can indicate systems toward which the proposed Terrestrial Planet Finder (TPF) interferometer could preferentially detect faint flux from terrestrial planets.

At the present age of 5×10^9 yr, all the dust in our solar system is necessarily material recently released by collisions and sublimation of remnant planetesimals (asteroids and comets). An external observer of our system could infer the presence of planetary-mass objects both as the perturbers of asteroids and comets into crossing and star- grazing orbits, and as the cause of warps, asymmetries, density waves, empty annuli, and sharp edges in the populations of dust and dust parent bodies. One example is the resonant ring and wake of zodiacal dust trapped in the Earth's orbit (Dermott *et al.* 1994), seen by IRAS and COBE, while a second example is the well-known the warp in the β Pic disk plane, modeled as being due to a Jovian-mass planet.

8. Composition and Physical Conditions of Extrasolar Giant Planets (EGPs) and Brown Dwarfs (BDs)

The MIR is a very useful range for examining and characterizing BD and EGP structure and composition. The continuum across this region is provided by the collision-induced absorption of molecular H_2 and possibly by the absorption/scattering of particulates in the atmospheres of these bodies. The H_2 continuum will provide the best determination of the temperature structure in the upper atmospheres/photospheres of these bodies. Direct constraints on the temperature structure will link to various equilibrium and evolutionary models of these gas giants and thus constrain the size and mass of these bodies (Burrows *et al.* 1997). While BDs also show the 2.2 μm H_2 collision-induced fundamental feature, it is more likely that this feature is influenced by atmospheric dust particulates in the micron and submicron size range.

A variety of individual spectral features are also accessible in this spectral region. These include bands of H_2O and CH_4 in the 6–8 μm region, as well as rotational H_2O lines longward of 20 μm. High signal-to-noise spectra of these features in several objects will determine C/H and O/H abundances and establish the basis for models in which these constituents change with the mass and effective temperature of the object. In addition, there is a band of CH_3D whose detection would verify the expectation of deuterium depletion in BDs and differentiate between BDs and planets. Other spectral features in the 10 μm region include NH_3. Detecting NH_3 and characterizing its abundance would either verify the temperature-dependent equilibrium expected between NH_3 and N_2 in an H_2-dominated atmosphere, or demonstrate disequilibrium chemistry. Other disequilibrium species detectable in this spectral region at $R \approx 1000$ include C_2H_2, C_2H_4 and C_2H_6. Disequilibrium chemistry has already been demonstrated by the unexpected 5 μm detection of abundant CO in the relatively cold atmosphere of Gliese 229B (Noll *et al.* 1997). Further spectroscopy of other faint objects would characterize the extent to which disequilibrium chemistry prevails in these bodies, and the extent to which it requires the upwelling or upward diffusion of gas from the interiors of these objects.

While parts of this spectral range are accessible to ground-based observatories such as Keck, BDs are very faint and not likely to be characterized well spectrally (for $\lambda > 17$ μm, even objects as bright as the now familiar Gliese 229B are too faint for detection). For BDs in multiple systems and for EGPs, major advantages of NGST in this spectral region will be its ability to resolve a secondary body from its primary down to a limit on the order of 1-2$''$ in the MIR, and the much reduced contrast ratio (10^{-3} to 10^{-4}) for EGPs.

9. Summary

The "discovery space" of NGST can thus be significantly enhanced with an MIR capability, even allowing for the flood of information provided by precursor and coeval missions such as SOFIA, SIRTF, ALMA, and large ground-based optical, infrared, and submillimeter telescopes.

Acknowledgments. We thank Z. Haiman, L.C. Ho, M.A. Malkan, S.P. Oh, and B. Whitney for their inputs to the full report. This work was performed in part at the Jet Propulsion Laboratory, under contract with NASA.

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